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Reservoir-Geological Characterization of a Fractured Limestone: Results Obtained from the Geothermal Well St. Gallen GT-1 (Switzerland)

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ABSTRACT

St.Gallen is situated in the western Molasse Basin (MB), an orogenic foreland basin of the Alps. The aquifer is formed by Upper Jurassic carbonates. In the eastern Molasse Basin (Germany), these carbonates are often dolomitized showing high hydraulic conductivities. For several years, geothermal plants such as Unterhaching have been producing electricity and heat.

In 2009, the St.Gallen geothermal project started with a feasibility study based on a small quantity of data. Accordingly, production flow rates of 50 l/s should be possible at temperatures from 145 to 150°C. 3D seismic investigations concretizing the well design in preparation of the geothermal well were carried out. From March to July 2013, the St.Gallen GT-1 well was drilled into the Middle Jurassic down to a depth of 4450 mMD (4255 mTVD). According to plan, the NNE-SSW striking St. Gallen fault-zone could be drilled through in the Upper Jurassic section.

The potential Upper Jurassic aquifer was developed from 3992 – 4404 mMD. Yellowish-brown micritic limestones containing residues of siliceous sponges were developed here from 3992 – 4280 mMD, a dark-grey micrite with sponge needles (basinal limestones) from 4280 - 4375 mMD, sandy calcisiltites down to 4404 mMD, and Dogger rocks down to 4450 mMD. In place of the expected Quinter limestones (Helvetian facies), Swabian sponge mass facies were found. Dolomites causing the good permeabilities in the eastern Molasse Basin could be observed very subordinately. Indications of karstification, open porosities and fractures were only scarce. Increased quantities of transparent calcites could be observed only at 4070 mMD and from 4150 – 4210 mMD; white calcites observed from 4315 – 4335 mMD indicate a fault zone with closed fractures. Temperature logs and other parameters show anomalies in three sections indicating inflow zones.

The well St.Gallen Gt-1 was acidized several times in July and October 2013 and investigated hydraulically by means of injection and production tests. The produced deep water contains dissolved salts (TDS approx. 25 g/l) and gas. The hydraulic parameters and the structure of the reservoir could be determined by means of the tests. The pressure behavior curves indicated two closed boundaries correlating with faults in the St. Gallen fault zone. The hydraulic conductivity between the two peaks is increased here, but with a limited reach. The inflows are tied strictly to the faults.

1. INTRODUCTION

1.1 Aim of the study

The implementation of the St Gallen geothermal project started with the feasibility study submitted on 31.8.2009 (Kohl et al. 2009). Accordingly, geothermal aquifers were assumed at depths from 4 to 5 km with expected flow rates of 50 l/s at temperatures > 150 °C. It was already clear that the mentioned flow rates could be realized through faults only. However, the level of geological knowledge was very low for the St. Gallen Region. Malm, Muschelkalk and the crystalline basement were the prognosticated aquifers.

From January to April 2010, 3D seismic loggings were done by order of the municipality of St. Gallen which significantly increased the level of knowledge on the structure of the underground and provided information on the optimum site of the planned geothermal cogeneration plant. Thus, the geothermal well could be designed optimally. The drilling of the St. Gallen GT-1 well started on 5.3.2013 and finished on 7.7.2013 having drilled through the Malm. A micritic limestone was developed which was partly connected with a fault. The works were accompanied by extensive geophysical loggings. The unique data and findings resulting therefrom and characterizing a fractured limestone are the subject of this paper.

1.2 The Molasse Basin (MB)

The Molasse Basin is situated in S Germany limited by the Northern Limestone Alps or the Folded Molasse in the South, the Franconian Alb and the Swabian Alb in the North, the Bavarian Forest / Bohemian Massif in the East and the Swiss or French Folded Jura in the West (Figure 1). The basin is approximately 700 km long (WSW-ENE) and approx. 250 km wide (NNW-SSE). The main part of the Molasse Basin is situated on German territory extending to Austria, Switzerland and France. The Molasse Basin contains Oligocene and younger sediments which are 5000 m thick at the northern margin of the Alps.

300 million years ago, during the Permian, the present Alpine foreland consisted mainly of granites and gneisses (Bachmann et al. 1987). In the course of another several million years, this base rock was covered by Mesozoic and younger sediments from west to east. First clastic sediments were deposited during the Rotliegend and the Buntsandstein stages in the west of the Molasse Basin. Subsequently, the Muschelkalk sea transgreded from the North, extending the sediment cover towards the East. This tendency continued also during the Keuper and the Lower and Middle Jurassic, reaching approximately the present site of Munich.

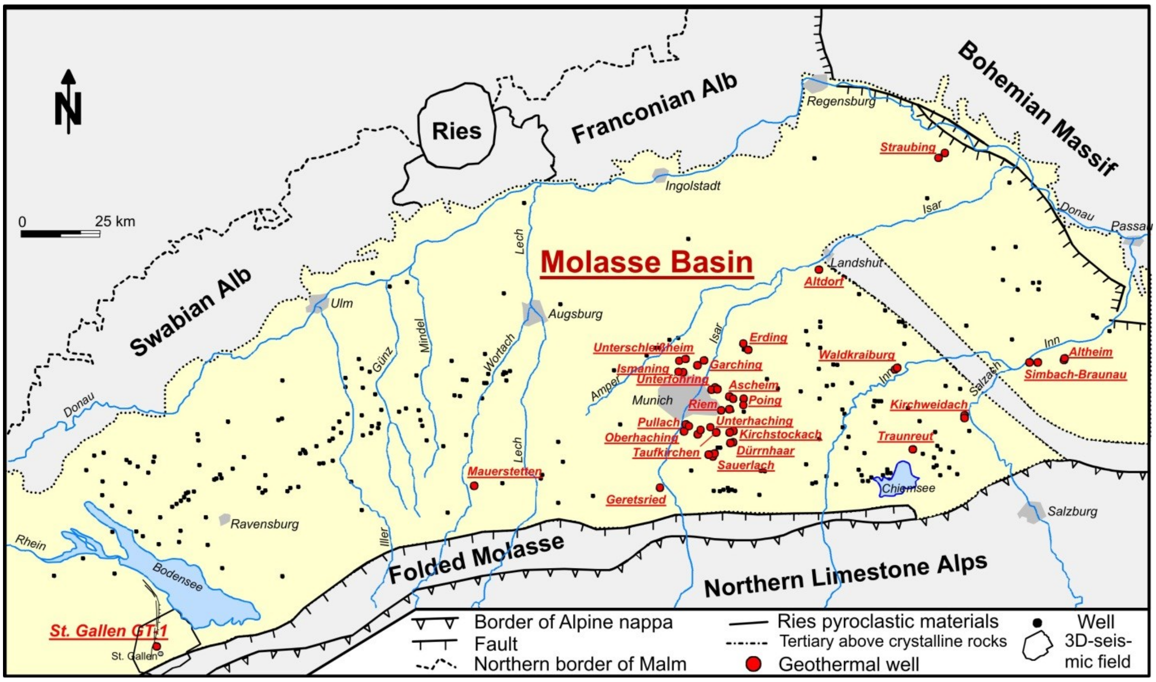

Figure 1: Distribution of geothermal wells in the Molasse basin (red), mostly used for power generation (after Wolfgramm et al., 2012). 3D seismic survey is centered at St. Gallen.

During the Malm, the sea had its largest extension (total flooding of the present Molasse Basin territory) reaching the Bohemian Massif and flooding it partially. In the South, the sea was rather deep, with the other parts being relatively shallow. The palaeo-landscape was characterized by coral and sponge reefs with lagoons in between. At that time, the Munich area was marked by distinct reefs.

Subsequently, the sea vanished almost completely from the present area of the Molasse Basin. During the Cretaceous, the sea advanced again from the South, being limited, however, to the present territory of Eastern Bavaria (largely around the present area of Munich). At the end of the Cretaceous and with the beginning of Tertiary sedimentation, the territory of the present Aline piedmont turned into a foredeep of the Alpide orogeny and the formation of the Molasse Basin began (Bachmann et al. 1987).

The Tertiary Molasse Basin itself has to be considered as an orogenic foreland basin of the Alps. Such basins were connected all over again with the Thetys. These effects are reflected in the sediments of the Upper and Lower Marine Molasse. When the marine influence was small, predominantly sediments of the Upper and Lower Fresh-water Molasse were deposited. Mainly sandstones, marls, mudstones, and limy fine-sandstones accumulated.

1.3 The Upper Jurassic Aquifer

During the Malm, totally different habitats existed on the territory of the present Molasse Basin which is reflected by the different formations of the Malm rocks. Developing from the South, alpine (helvetic) facies reached far into the present territory of the Alps interlocking with the Teutonic (Swabian) facies. The deep sea sediments of the Helvetic facies are characterized by bituminous Quinten lime. These platy to thickly bedded limes mark the clay marl and hornstone strata. Such formations advanced far into the East in the Malm Alpha (deepest part) drawing back again in western direction by the Malm Zeta.

There exists a SSE-NNW striking uplifted block of the base rock in the Landshut-Kehlheim region which formed an island in the Malm sea. Barrier and fringing coral and sponge reefs formed around this island, too. More reef systems formed on the present territory of Munich. Lagoons were situated in between these reef systems where sandy carbonate muds accumulated. These lagoons are characterised by fine interbeddings of marl and carbonate rocks.

The karstification of the Malm carbonates is the reason for the exceptionally good hydraulic properties of this most important geothermal aquifer in S Germany. Mainly, the karstification is restricted to sections with large fault systems and the carbonates of the reef facies showing already good conditions for the flow of meteoric waters. Moreover, sections with large fault systems for the transport of huge water quantities are known. The dumping of the South German Major Block is understood to be the cause of this karstification. The rocks were shifted underneath the Alps in the south and in the northern part of the Block either to the surface or very close to the surface allowing for penetration and drainage of water. The northern sections of the Malm in the Molasse Basin are karstified more as they were exposed longer to the surface. In the Swabian and the Franconian Alb, the Malm carbonates form rocks. Karstification can be observed here at numerous places.

Generally, karstification decreases from N towards S, so that predominantly fault zones act as flow paths in the South. But only in the South, the Malm reaches > 3 km and, thus, temperatures > 110 °C allowing for geothermal electricity generation. Due to the only insignificant karstification of the lime rocks in the South, faults have to be connected in order to achieve high productivities of the wells. Partly, the rocks are broken up heavily within these fault sections showing, in addition, several accompanying damage zones.

1.4 Geothermal energy use in the Molasse Basin

Geothermal development started in the Molasse Basin in 1938 already with the drilling of the HC exploratory well Füssing 1; the wells Füssing 2 and 3 were drilled in 1963/64. Along with the merely balneological use, the geothermal energy was exploited for heating as well. Between 1984 and 2004, more geothermal systems or thermal spas were installed in Erding, Altheim, Simbach-Braunau, Gallspach, Geinberg, Bad Schallerbach, Obernberg, Haag, Schlattingen, Kreuzlingen, Konstanz, Ravensburg, Pfullendorf, Tuttlingen, Waldsee, Unterschleißheim, Riem, and at other sites (Figure 1). In 2001, geothermal power was generated for the first time. All wells were located in either the Lower Austrian-Bavarian Basin, the northern part of the Molasse Basin, or in the Greater Munich area where the Malm is characterized by strong karstification.

With the drilling of the Gt Unterhaching 1a (2004) and Gt Unterhaching 2 (2007) wells, the Malm was explored geothermally for the first time in sections buried more deeply. The drillings were very successful (Wolfgramm et al. 2007) and triggered a boom in the region S of Munich. Power and heat cogeneration plants were built at Sauerlach, Dürrnhaar, and Taufkirchen (Figure 1), among others. Temperatures exceeding 120 °C at flow rates > 100 l/s are characteristic parameters (Agemar et al. 2014).

The exploration area was extended towards E and W by drilling the wells at Mauerstetten, Kirchweidach, Traunreut, Waldkraiburg, and Geretsried. In particular the extension towards W was very risky as according to documents available since 2010 at the latest (Bavarian State Ministry of Economy, Infrastructure, Transportation and Technology 2010, Birner et al. 2012), a significant decrease of the rock permeability from E to W or NE to SW has been known which was explained by the change of the Franconian to Helvetian facies. High rock permeabilities were tied here to either karstification or matrix porosity of the dolomitized limestones of the Franconian facies. Considering the productivity, the wells in the East were successful, but the temperature gradients were clearly partly lower than in the Munich area. The wells at Mauerstetten and Geretsried in the West failed. Actually, projects continue to be implemented in the surroundings of Munich and in the eastern Molasse Basin.

2. GEOTHERMAL PROJEKT ST. GALLEN

Among the projects implemented in the Molasse Basin, St. Gallen is situated in the West (Figure 1) and, thus, in the section where the matrix porosity of the Malm can be assessed as non-perspective. At the beginning of the project a limestone in Quinten (Helvetian) facies was expected as well as inflows in strongly fractured sections. In order to boost the prospects of success, the exploratory well was designed in a way considering also the Upper Muschelkalk and the Permian basement as potential aquifers as an alternative to the Malm. Here again, the fault zones were the target sections. In the case that the flow rates in the Malm would be insufficient, the well should be drilled deeper to test the alternative horizons. In order to guarantee an optimum progress of drilling, a 3D seismic investigation was carried out since the database was bad for the area under investigation.

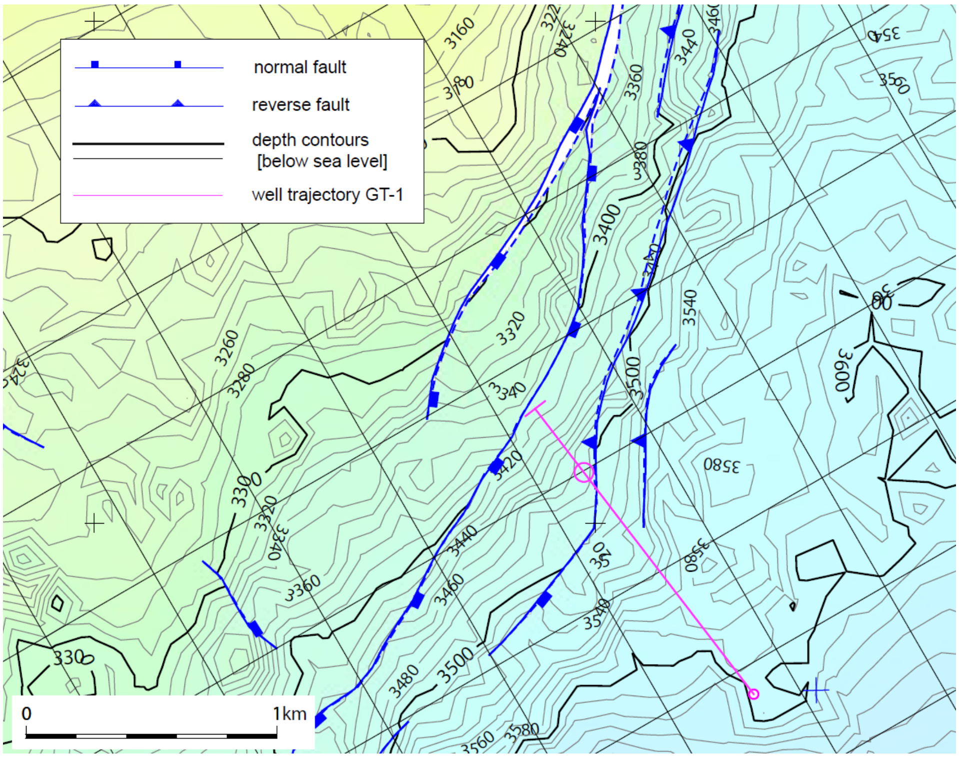

Figure 2: Structural plan of the Malm base resulting from 3D seismic analyses. Planned drilling site, target point and the point of penetration in the section of the upper edge of the Malm are documented (Status of 2012).

2.1 3D seismic investigations at St. Gallen

From 26.1.2010 – 06.04.2010, 3D seismic logging was done at St. Gallen. The logged area covered approx. 300 km^2, 2/3 of it were included in the interpretation (Figure 1). In the course of the seismic exploration, 6280 excitations were caused (6000 by means of vibrators, 280 applications of dynamite sources). The interpretation of the 3D seismic logs brought clarification on the structures in the underground (Figure 2). The depth position could be determined with the usual deviations of ± 5% and fault zones could be located precisely and presented in detail. The “west fault/St. Gallen fault zone“ was left from the two fault zones determined before from the 2D seismic logs denominated as St. Gallen Fault Zone (SFZ) in the following (Heuberger and Naef 2012). It consists of two just about parallel NNE striking faults at a distance of approx. 500 m (Figure 2, Figure 3). The interpretation of the results of the 3D seismic logs resulted in a more exact characterization of the fault zones. The coherence analysis shows that around the faults and in particular within the Malm strongly fractured rocks had to be expected. The drill path was designed in between two of the main faults (Figure 3). Below the top of the Malm it was corrected still a little towards the eastern (SE) fault.

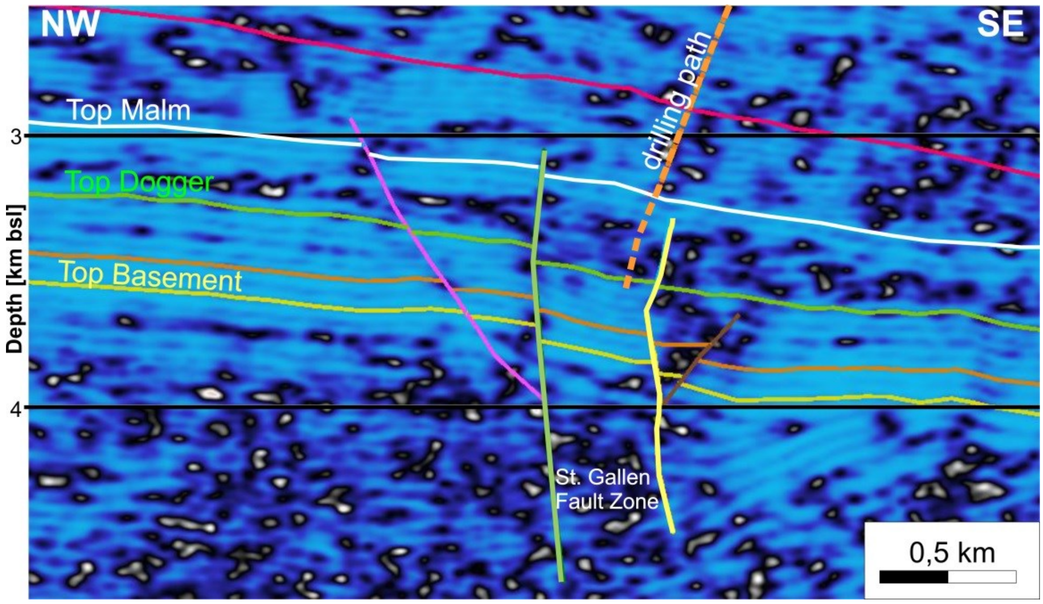

Figure 3: 3D seismic NW-SE similarity profile section across the St. Gallen fault zone incl. designed drill path; low coherence – dark, high coherence – light.

2.3 Stratigraphy, lithology, and technical well parameters of the St. Gallen GT-1 well

The stratigraphy of the St. Gallen well is presented in Figure 4. The Malm as the target horizon is situated beneath 3810 m thick Molasse deposits consisting of Miocene and Oligocene sediments. The stratigraphic sequence begins with 4 m thick anthropogenic deposits followed by 232 m thick marls of the base zone of the Upper Freshwater Molasse (USM) with an embedded approx. 15 m thick conglomerate (calcareous nagelfluh). The St. Gallen Formation (Upper UMM) consists mainly of conglomerates (barrier, Dreilinden and Freudenberg nagelfluh) with an integrated platy sandstone and a slaty marl zone. The Luzern formation (Lower UMM) extends between 347 and 768 mMD consisting mainly of glauconitic calcareous fine sandstones interstratified by thin coal layers. Marl layers are found more widely especially in the upper section. The border with the underlying Upper Aquitane marl zone is given by a base conglomerate. The Upper Aquitane marl zone consists mainly of colored marls interbedded by a few thin calcareous fine sands. The further layers of the granitic, carbonate-rich and colored molasse are rather monotonous, the shares of calcareous fine sands vary, respectively. Altogether, they form the Upper Freshwater Molasse (LSM). An up to 50 % share of transparent calcites of joints in the cuttings has to be emphasized within the range from 2420 – 3325 mMD. This section is assigned to the so called triangle zone – a tectonically disturbed section in front of the Alps. The Horwer sandstone (a pyrite-rich calcareous sandstone) and the Grisiger marl (a clayey marlstone) are situated at the base of the molasse which is assigned to the Lower Marine Molasse.

Platy limestones follow directly underneath the Grisiger marl which can be assigned to the Swabian spongious lime facies. This layer extends between 3992 and 4280/4290 mMD and consists of yellowish-brown limestones with sponge residues, tuberoids, and other fossil content. This layer is followed by grey to dark-grey limestones of the basin facies which are denominated as well bedded limestones. The calcareous marls and Impressa marls were developed down to a depth of 4402 mMD which are separated from the Dogger by a 2 m thick glauconite sand marl.

The rock overlying the Dogger is interstratified by alternating lime-, marl-, and claystone layers with embedded iron ooids down to a depth of 4424 mMD, the underlying rock consists of iron ooid sandstone (Wedelsandstein formation). From 4423 m downwards, a middle-grey claystone was drilled through. The final depth achieved was 4450 mMD or 4253 mTVD. The well was completed according to the parameters given in Figure 4. The reservoir section of the St. Gallen GT-1 well was secured by means of a partly perforated liner. The St. Gallen GT-1 well was deviated after 680 mMD towards 320 ° with an inclination of approx. 20°.

3. UPPER JURASSIC GEOTHERMAL RESERVOIR AT ST. GALLEN

3.1 Stratigraphy, lithology of Upper Jurassic carbonates

The lithologic-stratigraphic structuring of the Malm was based on the analyses of cuttings which were taken at 5 m intervals in the normal case as well as of side wall cores taken from the section ranging from 4100 to 4419 mMD. Thus, the lithologic structure could be determined already by means of the cuttings. Microfacial types, sediment structures and the biogenic content were identified by means of the thin sections (Steiger & Uhlig, 2014). Figure 5 shows some selected examples of the petrographically different units.

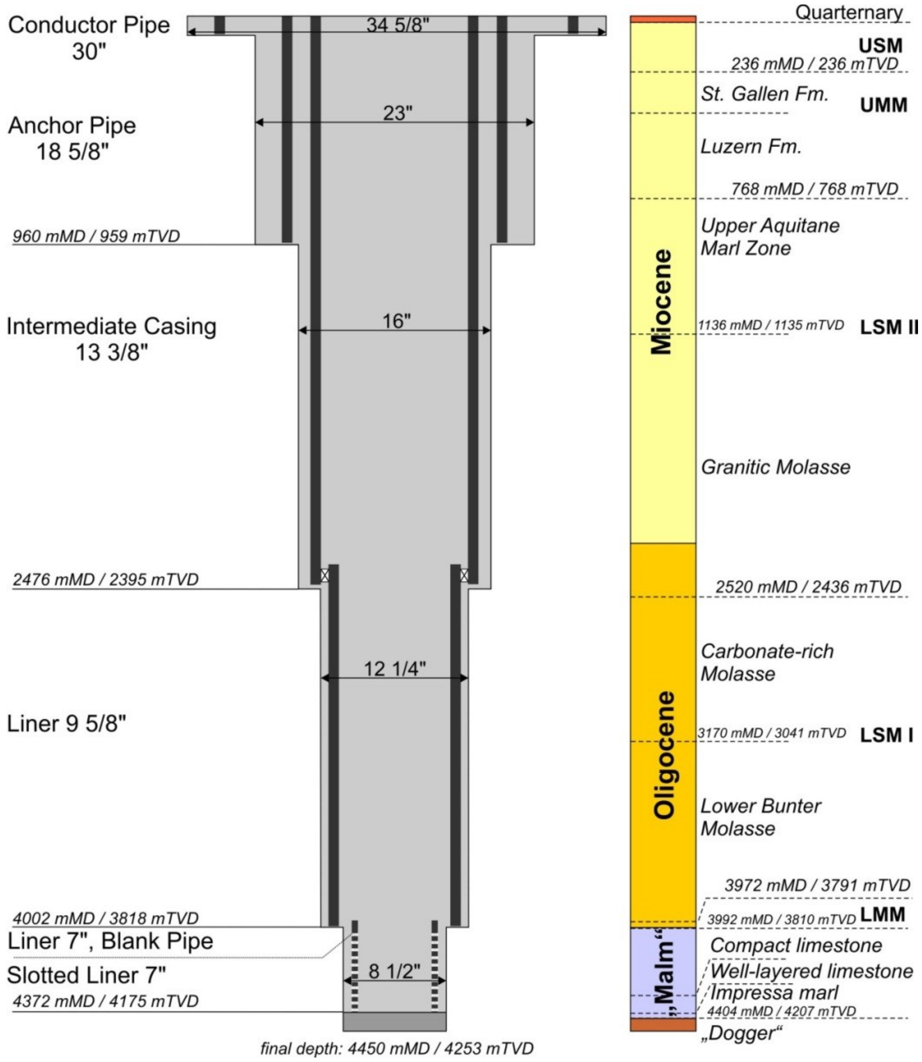

Figure 4: Brief well-log, well parameters and casing of the St. Gallen GT-1 well, TVD: total vertical depth, MD: measured depth.

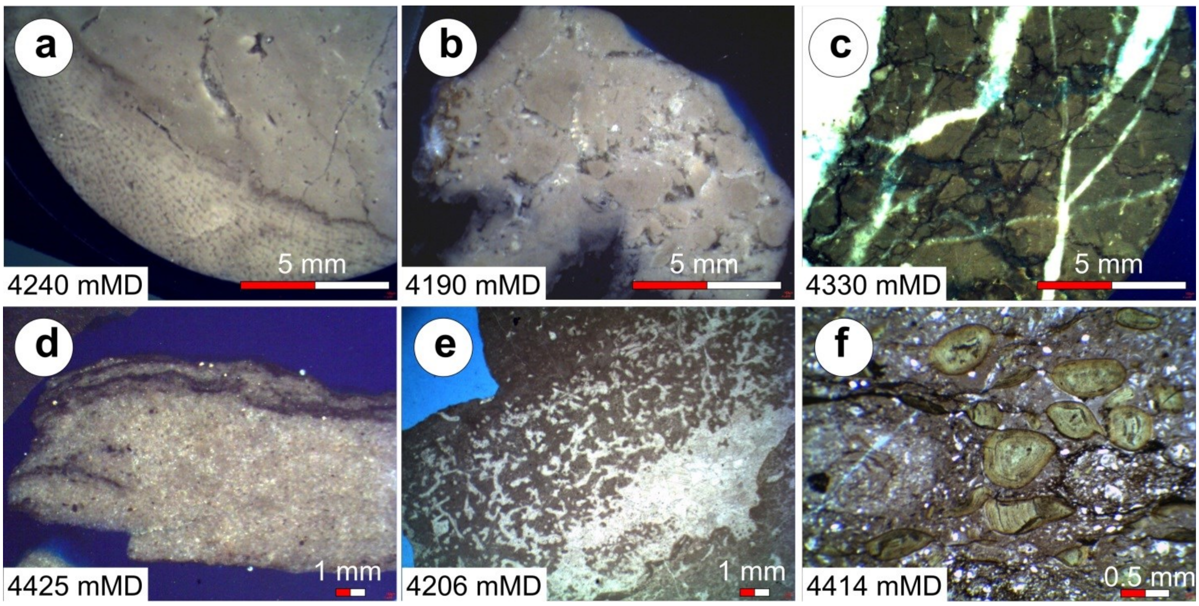

Figure 5: Top: Photos of the side wall cores, a – platy limestones, yellowish-brown micrite with sponge structure, b – Bankkalke, yellowish-brown micrite with intercrystalline porosity, c – Impressa marl with calcite fractures; bottom: photos of thin sections, coulored with Alycerin-S: d - Dogger sandstone, e – platy limestones, micrite, sparite with sponge structures, f – Dogger siltstone with iron ooids

The Malm is characterized by micritic spongious limestones transforming into pelagic micrites towards the top which is shown by an increasing influence of high-marine fauna elements and deepening of the shelf area. The micritic spongious limestones can be assigned to the Swabian facies. The Upper Jurassic sequence underneath the pelagic micrites is characterized by a two-speed lithologic evolution. Detrital calcareous clasts of a partly oolithic nature dominate in the upper section. But, the transported components are fixed microbially shortly after deposition. The fine sand content of the calcareous micrites increases towards the base, and limy siltstones bearing glauconite grains at the Malm base and a little further below yellowish-green iron ooids are formed in the section of the Dogger/Malm border. According to the contained bio-inventory, the Malm can be subjected to a triple subdivision stratigraphically based on the coenozonic fossils. The (1) Saccocoma coenozone extends from 4000 to 4070 mMD, the (2) radiolarian and Bositra coenozone reaches from 4070 – 4180 mMD, and the (3) Protoglobigerina coenozone was proven down to a depth of 4415 mMD (Steiger, in prep.).

The dolomitization of the Malm required for an intensive matrix porosity is to be observed very rarely only. Authigenic dolomite crystals (idiomorphous rhomboeders) appear in micritic facial types at depths around 4,355 – 4,400 mMD. However, the dolomite rhomboeders are dedolomitized exclusively. Nowadays, they exist as pseudomorphoses from calcite to dolomite. The second form of the dolomitization is a pressure-solution dolomitization. Its formation can be observed within stylolites. Mostly even-grained rhomboedric crystals are densely packed within the pressure-solution seams (Steiger and Uhlig, 2014). They are found at depths ranging from 4,345 and 4.355 mMD and are dolomitized just as the authigenic dolomites. Finally, a minor intercrystalline porosity exists locally within the limestones (Figure 5b).

Based on lithologic findings and logging data, inflow zones in the Malm can be identified. Temperature logging data is important here. Negative temperature gradients indicate inflow zones. In addition, the spectral gamma log delivers good information. The thorium activity within the Malm varies from 3.3 to 6.3 API, two thin section show peaks of 95 API or 35 API. Increased activities are typical for the Dogger (65 – 125 API). The Th anomalies are interpreted as faults reaching down into the Dogger or even deeper. Sonic speeds determined by sonic log indicate sections with lower values which may be potentially water-filled porous/fractured sections. Among others, a distribution of clear fractured calcites across the Malm course results from the analysis of the cuttings. Increased shares indicate faults. Three potential inflow zones result from a corresponding analysis (Figure 6):

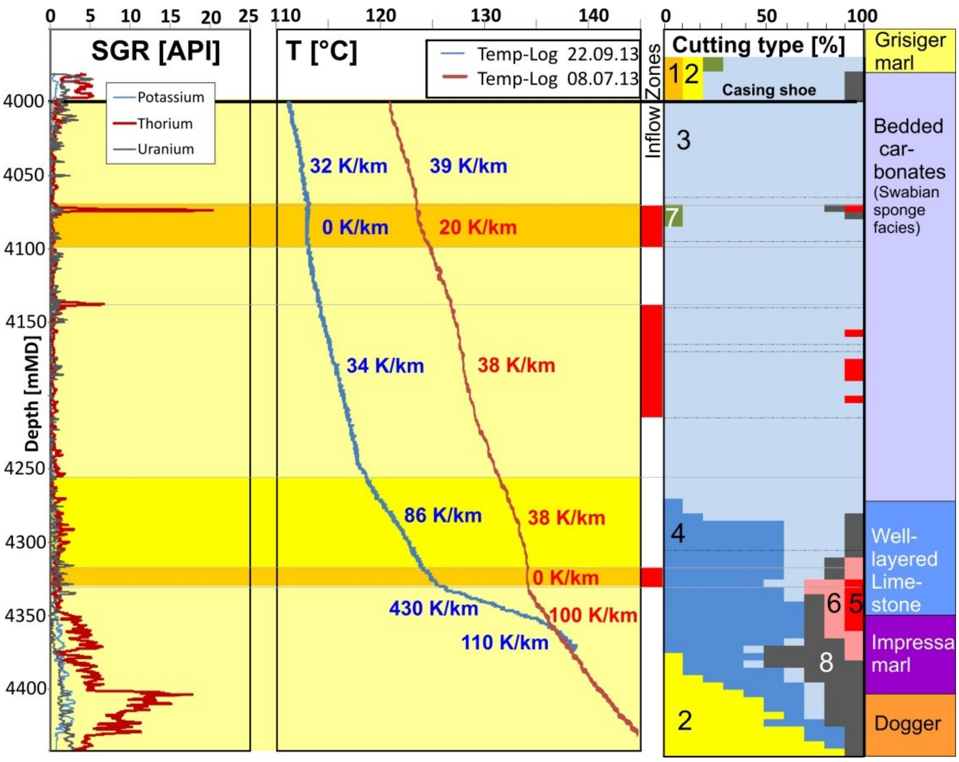

Figure 6: Malm inflow zones in the St. Gallen GT-1 well according to logging and greatly simplified analyses of cuttings (1 – siltstone, 2- sandstone, 3 – yellowish-brown micrite, 4 – brownish micrite, 5 – clear fractured calcites, 6 – white fractured calcites, 7 – marl, 8 – black particles and pyrite).

Zone 1 (4070 – 4095 mMD): Increased shares of transparent calcites; the 95 API Th anomaly, a strong temperature anomaly and the enhanced presence of dark cuttings indicate the existence of a fault zones which must be active hydraulically. It is the/a main inflow zone of the St. Gallen GT-1 well.

Zone 2 (4140 – 4215 mMD): Increased shares of clear transparent calcites, a strongly varying temperature gradient and often low sonic speeds (sonic log) indicate a potential inflow zone/section.

Zone 3 (4310 – 4330/4335 mMD): A negative temperature anomaly, increased shares of transparent calcites and strong fracturing (Figure 5c) indicate an inflow zone. Evidence against the existence of an inflow zone are the mostly higher velocities and the fact that the calcites of joints are mostly white thus indicating closed fractures.

In total, an inflow length of approx. 70 to 90 m is assumed. The main inflows are restricted here to fault zones at depths of 4070 mMD and 4140 mMD.

3.2 Petrography and petrophysical parameters

The major part of the Malm carbonates in the eastern Molasse Basin consists of dolomite showing matrix porosities of up to 20 %. The porosities averaged across the overall Malm length range from 6 to 13 % (Wolfgramm et al. 2012). These porous dolomites have a big share in the overall productivity of relevant wells. Inflows from limestones were proven for sections only where faults occur. 95-99 % of the St. Gallen Malm consists of limestone. That is why matrix porosities were not to be expected.

Porosity, permeability, density, pressure resistance, friction angle µ and cohesion were determined by means of laboratory analyses of the side wall cores taken from the Malm section. The analyses show differences according to their lithologic correlation. So, a pressure resistance of 320 to 350 MPa was determined for the samples of the compact limestone (Figure 4) with a cohesion of 90 to 97 MPa and a friction angle µ of 0.6. The porosities were between 1.8 and 2.4 %, the permeabilities of max. 0.02 mD were low, accordingly. The well-layered limestones show normal pressure resistances of 190 MPa, with a cohesion of 40 – 50 MPa and a friction angle µ of 0.9. Here, the porosities and permeabilities were slightly higher (2.3 – 5.4%, max. 0.05 mD). In the Impressa marl, the pressure resistances of 100 to 110 MPa with a cohesion of 20 – 30 MPa and a friction angle µ of 0.6 – 0.9 were significantly lower than in the overlying layers. The porosities were highest with 4.8 – 5.8 %, but the permeabilities were lowest, i.e., < 0.01 mD. In Summary, it can be stated that the Malm at the St. Gallen site consists of a dense micritic limestone. Inflows are only possible via faults.

3.3 Structural model

There is a prominent NNE-SSW striking fault zone, cross-cutting almost the entire Molasse Basin between the Bodensee and the city of St.Gallen (Heuberger and Naef 2012). This zone, termed here St.Gallen Fault Zone (SFZ), is more than 30 km long and consists of normal faults interpreted from 2D seismic data. After 3D seismic data: The SFZ is defined by an up to 1 km wide zone mainly comprising 70-80° ESE-dipping normal faults and local reverse faults. The northern part strikes N-S to NNE-SSW and delimits a Late Paleozoic to Tertiary graben to its east. The eastern edge of this graben is represented by the Roggwil Fault Zone (RFZ) consisting of NW-dipping normal faults. The southern part of the SFZ strikes NNE-SSW and exhibits significantly less faults throw. Here, the SFZ rather represents a flexure zone with only small segments of normal faults offsetting mainly the Lower Mesozoic units (Heuberger and Naef 2012). Heuberger and Naef (2012) postulated for the St.Gallen-Bodensee region that the post-OSM deformation must have taken place in a strike-slip to normal faulting regime with compression in NNW-SSE direction and extension in WSW-ENE direction. The same principal stress directions were derived from fault plane solutions of recent seismic events in NE Switzerland (Kastrup et al. 2004). With this stress field it is obvious that the faults of the SFZ are ideally oriented (at an angle of about 30°) to have been reactivated in a transtensional mode (Heuberger and Naef 2012).

4. WELL TESTING

4.1 Test design and implementation

The hydraulic tests at St. Gallen were designed in a way which is typical for the other geothermal wells in the Molasse Basin (Figure 1). After a (1) cleaning lift (2) acidizing was planned in order to stimulate the well (cf. Wolfgramm et al. 2012a), followed by a stepwise production test. The planned test method was the gas lift (BOP shut, Figure 7a). For that, air should be forced into the well via a 5 1/2“ drill pipe by means of compressors, thus initiating the production of the fluid. On 12.7.12, temperature logging was done for identification of the inflow zones prior to the beginning of the test. The analyses of the cuttings and the FMI logs as well as the fact that no mud losses were observed while drilling lead to the assumption that the rocks were hydraulically impermeable. Afterwards and based on the experience gathered from the drilling of the Mauerstetten well it was decided to carry out an injection test before acidizing in order to prove the absorption capacity regarding the acid. This injection test was carried out successfully as a stepwise test on 14.7.13. Here, the static losses increased from 123 l/s to 5 – 7 m³/h. Afterwards, acidizing was carried out in two steps, subsequently the well was prepared for the production test. While running in the p/T tool by wireline, gas entries occurred unexpectedly. The well was closed and well control actions were taken. By means of bullheading, water and later also strong mud were injected to displace the gas. This succeeded, but the works resulted in seismic activities with a seismic event with a magnitude of 3.5 which was associated with a pressure drop in the well. The well was secured and – having redirected the project – a gas-water test was planned. The countermeasures taken with regard to the gas entries lead to an „up-sanding“ of the well up to the shoe with acidizable material. The well had to be cleaned again which was done down to a depth of 4372 mMD, afterwards the aquifer was secured with a 7“ liner, whereas the section from 3975 – 4020 mMD was covered by blank pipes and from 4020 – 4372 mMD by means of perforated liners (Figure 4). The gas-water test started on 14.10.13 with a clean-up test. For that, the test was prepared in the underground according to the downhole shut shown in Figure 7b. A 5 ½“ drill pipe was installed down to the shoe and secured by means of a packer. It was possible to open and close the well below via a test valve. The measured values were recorded via memory tools which were placed in a gauge near the packer. The production was initiated by means of nitrogen injection via a 1 ½“ coiled tubing (CT). Above ground, the test was prepared as shown in Figure 7c.

Via choke manifolds it was possible to lock the well above ground. The produced water-gas mixture passed a heat exchanger; the flow rates of the gas and the water were measured by a multi-phase flowmeter manufactured by the company Schlumberger. Afterwards, the fluid passed a separator. Then, the gas passed another separator and was flared. The water was fed into tanks. From there it was disposed off into a 7500 m³ pool having passed another heat exchanger. The fluid parameters were measured here, and water samples were taken regularly. After the first clean-up test – which resulted in very low inflows – acidizing was done by means of CT. After a cleaning lift and more acidizing, the stepwise test started, with recovery measurements in between the individual steps, respectively. The test could be implemented successfully and was completed with downhole sampling on 2.11.13. The seismic activity ended with the beginning of the test.

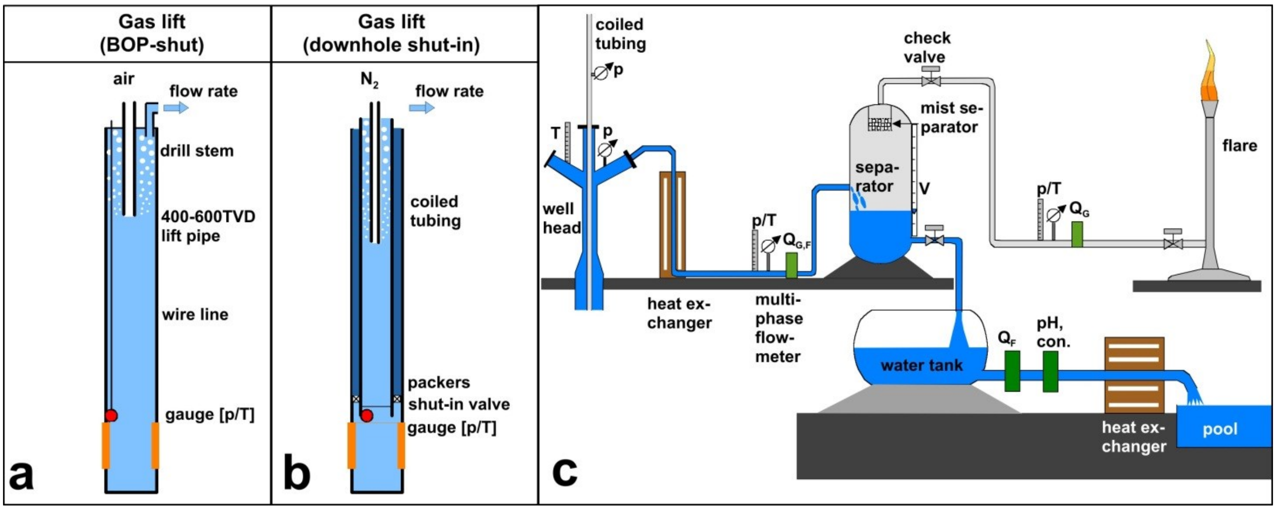

Figure 7: Schematized test design of the St. Gallen GT-1 well, a:– underground installation of the planned airlift test in 07/13, b: underground installation of the gas-water test in 10/13, c: surface installation of the gas-water test in 10/13, Q_F – water flow rate, Q_G – gas flow rate, Con – conductivity of water, p – pressure, T – temperature

4.2 Test data

With the first injection test of the well on 14.7.2013, the injectivity could be improved to approx. 0.6 l/(s*bar). Acidizing resulted in another improvement to 1.2 l/(s*bar) (instationary).

The gas-water test of October 2013 showed several “steps”. After the injection of nitrogen, the flow rates and temperatures developed in a very similar way in all steps of the test. The (1) slug flow phase was followed by (2) a phase of continuous water production. After a few hours, a small (3) „gas kick“ occurred always which was followed by a (4) continuous gas and water production (Figure 8). In this last phase, the injection of N_2 could be finalized by means of CT, then a natural gas lift took place. In particular the last one of the four production tests is important which lasted three days. Here, a flow rate of approx. 6 l/s was achieved at continuous water production over a period of around 50 hours. But the rate still decreased continuously (Figure 8).

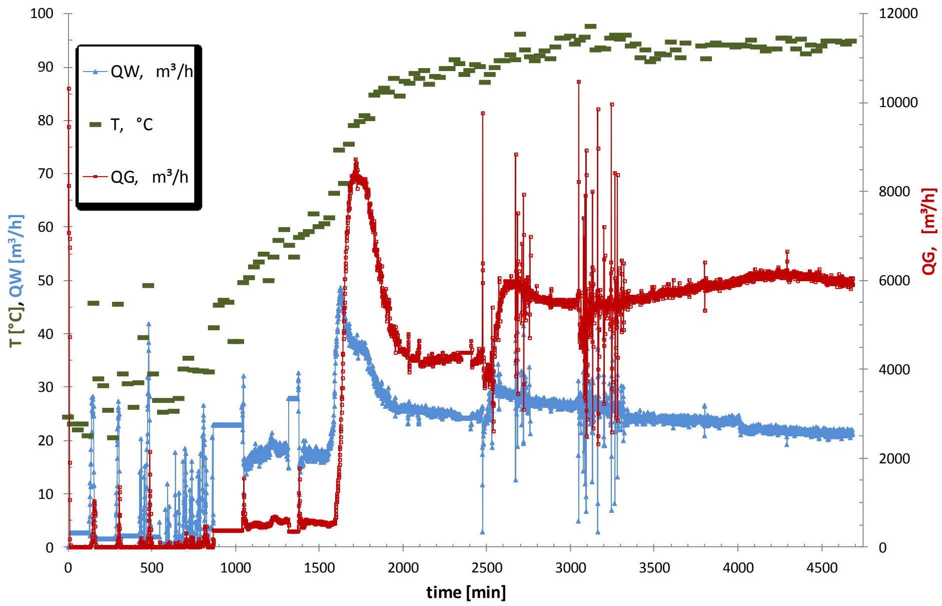

Figure 8: Flow rates of gas and water from production test 4, 25.-28.10.13, QW – water flow rate, QG – gas flow rate, T temperature at the well head.

At the end of this last production phase, the gas production flow rate was approx. 6000 Nm^3/h. The pressure drop in the aquifer was about 150 bar (Figure 9). The achieved, already stationary production temperature at the well head amounted to 95 °C (Figure 8). However, the max. production temperature at the depth of the aquifer top was 144.8 °C. At the depth of 3785 mTVD, the initial static pressure is approx. 371 bar.

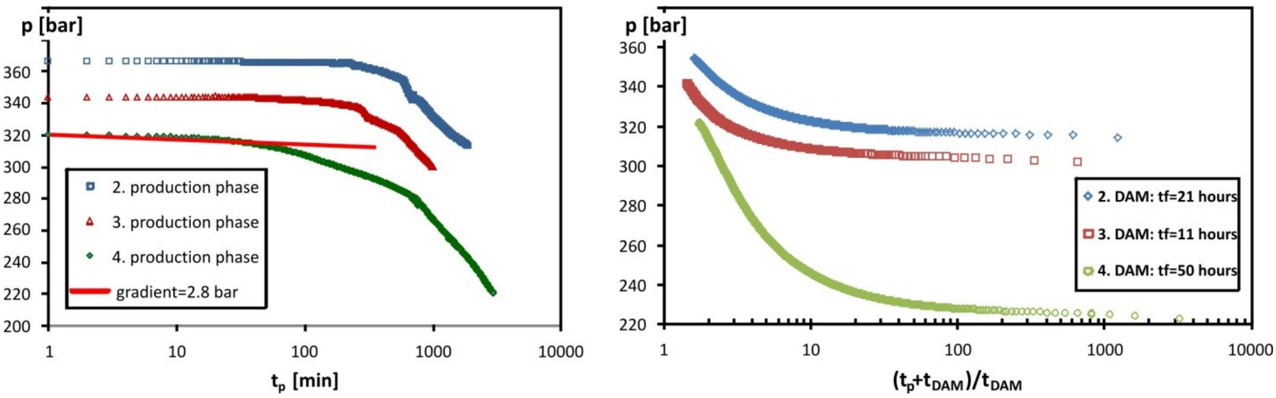

Figure 9: Pressure development during the last three production phases (left) and the corresponding pressure build-up curves (right), DAM pressure build-up.

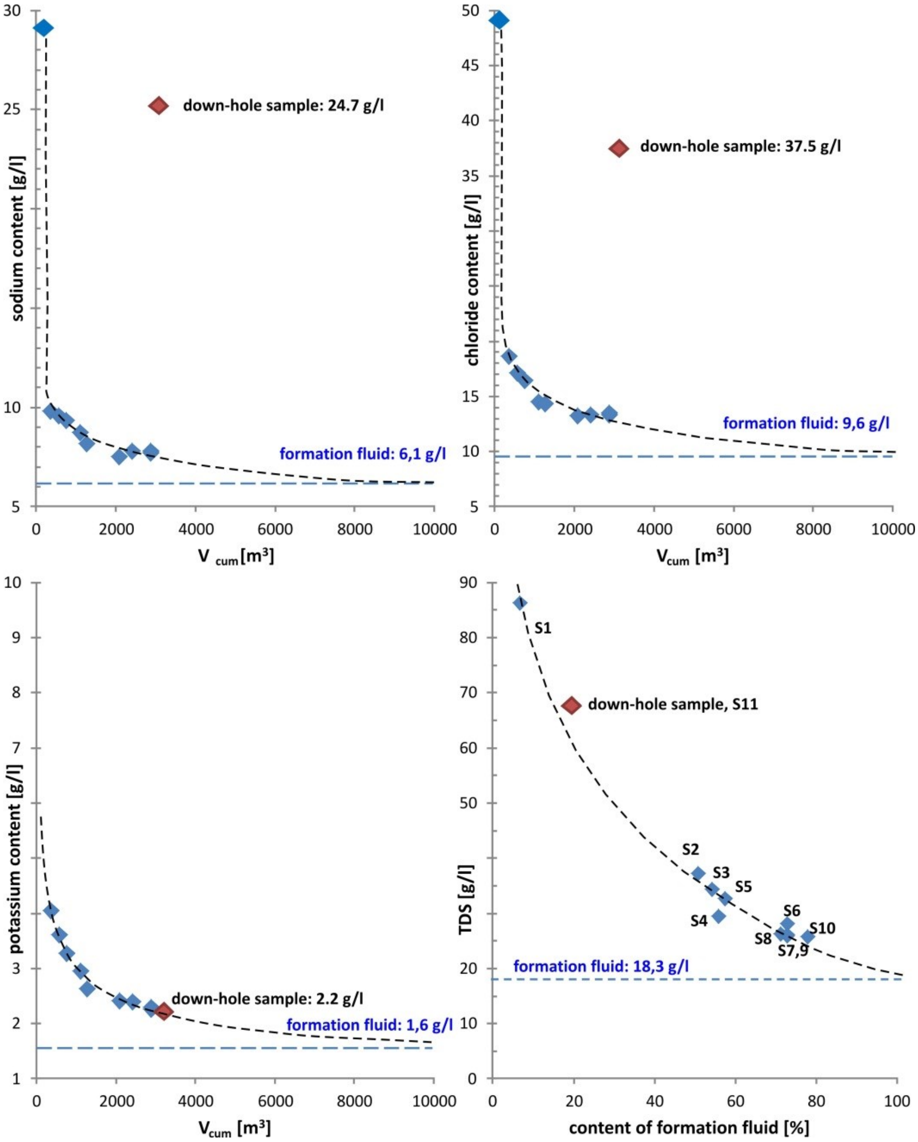

Figure 10: Development of relevant fluid parameters during the gas-water test vs produced fluid volume.

4.3 Aquifer fluids and gases

During the gas-water test, water and gas samples were taken and analyzed regularly. In addition, the pH value and the electrical conductivity were measured continuously (every minute). During production a gas sample was analyzed every two hours by means of a gas chromatograph (field measurements) for C1 – C4 and CO_2. Data from the analyses of 10 water samples taken in the production phases as well as of a downhole sample taken upon the completion of all tests is available. In addition, the water of groundwater well was analyzed. Furthermore, analyses of 9 gas samples are available, whereas one downhole sample was taken and two more samples were taken as pressure samples (p > 4 bar). All the gas analyses show a dry gas and a sweet gas (approx. 94.0 % CH_4, 4.8 % CO_2). The produced gas represents the reservoir gas. When evaluating the water samples it had to be considered that an amount of approx. 4000 m³ of fluid (well water mixed with approx. 140 g/l NaCl, density 1.08 g/cm³) had been fed into the well for stabilization over a period of about 2 months. The total fluid volume produced during the entire test amounted to approx. 3000 m^3. This is reflected by the data (Figure 10). The extrapolation shows that the ion concentrations decrease with increasing produced fluid volume which documented for the examples of sodium, chloride, and potassium (Figure 10). Here, the chloride concentration appears to aim at a plateau value of 9.6 g/l and that of sodium at 6.1 g/l. It results from the analyses that the sodium and chloride concentration accounts for about 80 % of the total dissolved content. Accordingly, the TDS content of the formation fluid should be approx. 18 g/l. In parallel, the share of the injected fluid in the produced fluid was estimated through the analysis of isotopes and tritium. So, the tritium content of the well water amounts to 5.9 ± 0.8 TU. The share of the formation fluid can be determined from the ratio of the tritium content of the produced water and the water of groundwater well. It is plotted in Figure 10 (bottom, right) versus the measured salinity. The extrapolation results in a salinity of the formation water of approx. 18 g/l which is in line with the value determined above. The special ranking of the analysis of the downhole samples has to be emphasized. The values should comply with the trend of the test data which is the case regarding some parameters such as potassium, magnesium, and calcium.

4.4 Test interpretation

The test data (Figure 9) show a bordered aquifer. Different borders of an aquifer are reflected by different, characteristic, standardized pressure curves. In Figure 11, some potential types of borders were selected and the relevant standardized pressure curves are presented. From the comparison of the measured pressure build-up curves (Figure 9, right) with the model type curves (Figure 11, top, right) it results for St. Gallen that the reservoir – according to models 1 and 2 – is bordered by two parallel impermeable faults with the well sited in the center or towards the border which is confirmed by the flow pressure curves. Moreover, these show that a near-well radial-symmetric flow can be distinguished from a parallel flow at a distance from the well. The determination of the permeability thickness for water results in 1 Dm for the near-well zone, and in 0.038 Dm only for the zone at a distance from the well. The permeability thickness for gas is lower by the factor 9. Considering the determined test data, the assumption that the compressibility for water-bearing, dense, porous rock is $c = 9 * 10^{-5}$ bar^{-1} and the viscosity is 0.213 mPa*s under reservoir conditions and the other values for porosity and reservoir thickness described above, the distance of the impermeable borders/faults can be calculated. These result in 104 m regarding the nearer border and 366 m to the more distant border. I.e., the developed aquifer is bordered by two parallel faults which have an internal distance L of approx. 470 m. This goes amazingly well together with the structural picture according to which the well GT-1 was drilled between two subparallel faults with an internal distance of approx. 500 m (Figure 2, Figure 3).

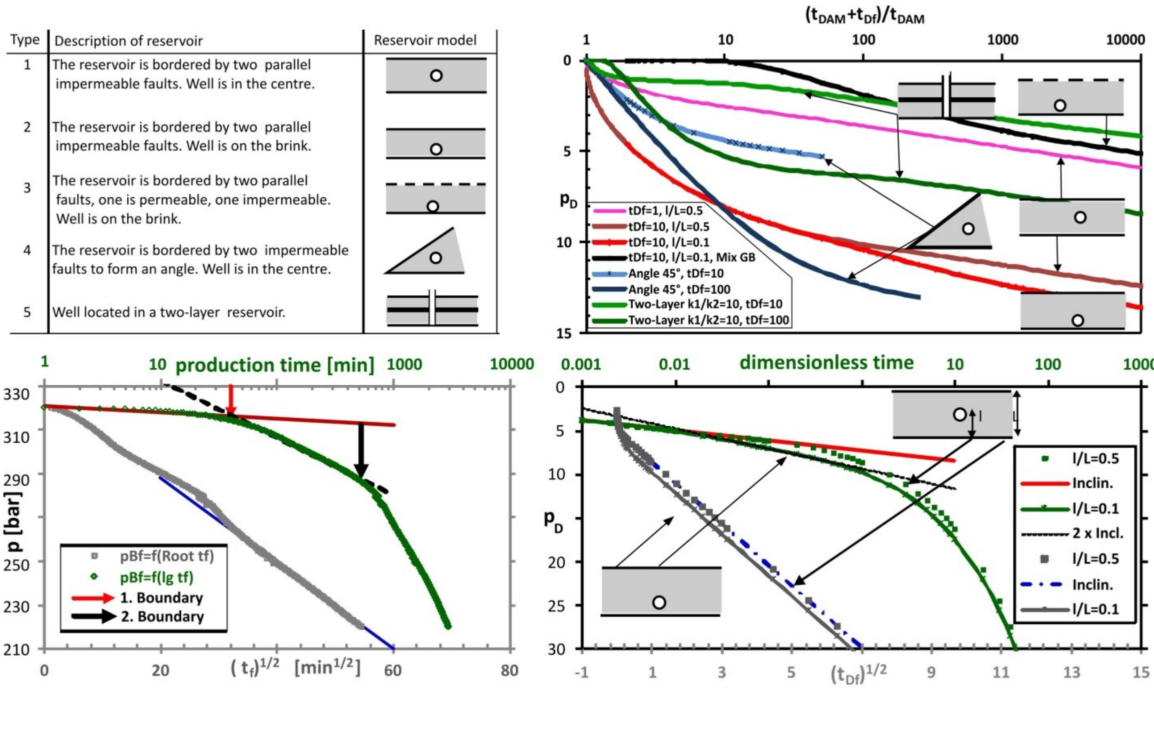

Figure 11: Potential reservoir models (top left) and corresponding standardized pressure build-up curves (top right): standardized flow curves for the relevant reservoir models 1 and 2 (bottom right) and the measured flow pressure c urve of the 4th production phase (bottom left); t_{DF} – standardized period of production.

5. DISCUSSION

5.1 Origin of the fluids and gases, geologic-hydrogeologic model of the St. Gallen site

An important question refers to the origin of the co-produced natural gas which consists of 94.1 % methane, 4.8 % CO_2, 0.88 % nitrogen, and 0.3 % higher HCs. H_2S was proven in one sample only with 0.0234 vol%. The isotope data of the gas indicate a sapropelic highly coalified parent substance (vitrinite reflexion >2 % R_0), methane formed thermogenically, the identified kerogen types are II and III. The origin of the CO_2 cannot be determined reliably. Here, the interaction of the carbonate rocks (Malm) plays a role. At St. Gallen, only the Carboniferous coals and Autunian shales occur among the HC source rocks known in Switzerland. Both should exist in the Permo-Carboniferous trough determined by 3D seismics. Gases enter via fractures. Reservoir rocks can be – apart from the "fractured reservoir Malm" Trigonodus dolomite, Melser sandstone (Muschelkalk), Dogger Beta sandstone or Rhaetian sandstone. The determined static pressures of approx. 371 bar at the top of the Malm indicate that the gases are stored in a fractured reservoir in the Malm.

Analysis of the waters resulted in a water of the Na-Cl type with a salinity of approx. 18 g/l. With a view to deviations caused by drilling-engineering requirements, the ratio of the main ions indicates a palaeo-marine water. Considering the composition of the waters in other wells in the Molasse Basin it has to be stated that low-saliferous infiltration waters with salinities of mostly < 1 g/l (Birner et al. 2011) dominate in the Munich area and in the eastern Molasse Basin (Figure 1). The salinities increase towards SE indicating less mixing with meteoric waters. It may be due to less karstification and lower matrix permeabilities of the Malm. The St. Gallen waters follow this trend as well.

It results from the interpretation of the water analyses that two major inflow/infiltration zones must exist. This is shown by trend changes in the development of the water conductivity when changing from continuous water production to combined gas-water production (Figure 8). Accordingly, higher mineralized water (higher conductivity) is produced at first from a fractured zone. Preferably, the highly saliferous drilling mud (140 g/l NaCl) was injected before in this zone. Because of the increasing drawdown of the piezometric level during production, the relevant fractures close as a consequence of the increased effective tensions. The fluid is now produced from a different section via which the gases flow in as well. This fluid corresponds rather to the formation water as here less drilling mud was added. Upon completion of the test, the piezometric level increases again, the effective tensions decrease. The fractures in the first inflow section open again, the concentration of the water balances in the well with the higher saliferous waters from the fractured zone. These waters were produced when taking the downhole sample. As the increased salinities of the downhole sample are mainly due to sodium and chloride and the tritium contents of the downhole sample are increased, this theory of the two inflow sections is supported. However, a more precise differentiation is not possible.

5.2 Fractured micritic limestones as aquifer

At St. Gallen, a hard micritic limestone – partly in disturbed deposits – was drilled through at a depth ranging from 3992 – 4280/4290 mMD. The matrix porosities and permeabilities of the investigated side wall cores are very low. Inflows are tied to the proven fault zones. It became evident at similar sites that high permeabilities in micritic limestones > 1 mD are found only in a damage zone of a fault which is close to the fault core (cf. Agosta et al. 2007). Mostly, this fault core is hydraulically impermeable. Moreover, the pressure resistances are very high – in particular those of the platy limestones. Inflows from the matrix can be excluded.

Based on the 3D seismic investigations, the St. Gallen GT-1 well developed the Malm in the St. Gallen fault zone which is directed NNE and shows a high slip and dilation tendency because of the recent stress field. Control works in the wells which were connected with massive water injections lead to a magnitude 3.5 seismic event which indicates an activity of the fault zone. The fault zone is limited by two marginal faults. The well is sited in between. The hydraulic tests showed gas and water inflows. It became evident that the short-term injectivities are better than the productivities by a factor of approx. 50. It could be derived from the pressure data that the reservoir is limited on two sides by parallel faults with an internal distance of approx. 470 m which coincides amazingly well with the 3D seismic data and the resulting drill path.

The proven water inflows of approx. 6 l/s and gas inflows of around 6000 Nm³/ are realized exclusively via the fractured aquifer in the Malm. Here, the near-well zone is hydraulically better by approx. 25-30 times than the distant zone. It cannot be stated clearly to which extent this can be referred to the stimulation measures taken before. Moreover, the fractures react strongly to changes of the water/piezometric level in the well. Already minor decreases of the water level lead to a reduction of the fluid pressure which is followed by an increase of the effective main normal tensions resulting in the "shutting" of the fractures. Because of the seismic activation of the St. Gallen fault zone during injection of the fluid, further investigations into the hydraulic behaviour of the fault zone are excluded. In the present condition, the fractured micritic sandstone is insufficient for geothermal uses. However, it has to be emphasized that this is not a principle statement on such systems. A positive example is Podhale in Poland where the wells deliver 125 l/s (Kempinska 2010). This aquifer consists of the Middle Triassic limestones. The secondary fracture porosity of 10-20% and intrinsic permeability up to 1000 mD supported by the presence of fractures and voids of karst origin if of main importance to high production from the wells (Kempinska 2004). In contrary, the values of primary porosity and intrinsic permeability reach up to 3-4% and 0.01-1 mD, respectively.

5.3 Comparison with the other geothermal projects in the Upper Jurassic of the Molasse Basin

The Malm in the Molasse Basin is the most prominent geothermal aquifer in Germany. Numerous wells were drilled producing deep waters at high flow rates (Birner 2012, Bavarian State Ministry of Economy, Infrastructure, Transportation and Technology 2010). The Malm in the eastern, central and northern Molasse Basin is characterized by strong karstification which is due to the infiltration of meteoric waters in the Swabian and Franconian Alb (Figure 1) (Wolfgramm et al. 2012, Birner et al. 2011). The karstification decreases towards S and SW. In the area S of Munich karstification is due to faults. It is assumed that deep waters flow across these faults which are responsible for corrosion by mixing and dolomitization. The limestones of the Franconian facies are particularly suitable for such dolomitization. Wells which were not drilled through faults show mainly less productivities than wells drilled into faults.

The share of dolomite in the Malm carbonates in the Molasse Basin decreases towards SW and W. Inflows are exclusively referred to fault zones. Such a fault was drilled through at Mauerstetten, but it was not possible here to achieve sufficient productivities. At the St. Gallen site, a similar depositional environment was hit by drilling. Water productivities are insufficient for a „normal" geothermal exploitation at either site. At both sites, the Swabian facies were developed. At the St. Gallen site, dolomitization could practically not be observed at all, not even in the fault zone. Apparently, the diagenesis mainly in the fault zones is of decisive importance. More investigations are planned in this field. St. Gallen possesses an outstanding / unique data base on the topic „Fractured reservoir in carbonates“ which should be interpreted scientifically in the next years.

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